



holograms are used.

In a computer-aided Fourier transform hologram, a limited rectangular area including a pattern ("NOEL" as mentioned above) recorded in that hologram is divided into a matrix array of cells, so that information regarding a pattern portion corresponding to each cell site can be allocated to each cell, so that a pattern comprising a limited number of cells is projected onto a hologram area far away from it upon Fourier transform. As is the case with the pattern recording area, the hologram area, too, is divided into a matrix array of cells to record amplitude information and phase information at each cell site where the pattern to be recorded is subjected to Fourier transform.

In the Fourier transform computer-generated hologram with such pre-selected patterns recorded therein, a pattern in a form depending on direction is viewed upon reconstruction. For instance, when the two sides of the hologram are reversed to reverse the left and right sides while the top and bottom remain intact, a mirror image is viewed, in which a right-hand image is seen as a left-hand image. When the top and bottom and the left and right sides of the hologram are reversed while the two sides remain intact, on the other hand, an inverted image is seen, in which an erect image is seen as an inverted image.

Accordingly, unless, upon transmission holograms 2 and 3 comprising such computer-generated holograms mounted on a spectacle frame 1, their top and bottom and their two

sides are in proper alignment with the spectacle frame 1, then the viewer could not properly see the pre-selected pattern in a given form.

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#### SUMMARY OF THE INVENTION

In view of such problems with the prior art, the object of the present invention is to provide a viewing device such as holographic spectacles, which enables a given pattern to be properly viewed in place of light  
10 sources in a scene and is easy to fabricate and assemble with consistent characteristics, and a computer-generated hologram for the same.

According to the present invention, the above object is achieved by the provision of a holographic viewing  
15 device in which a computer-generated hologram constructed as a transmission Fourier transform hologram is fitted in a frame member, wherein at least one of phase information and amplitude information recorded in a certain predetermined peripheral site of the computer-generated  
20 hologram relative to an input pattern reconstructible from the computer-generated hologram is removed.

Preferably in the present invention, the computer-generated hologram comprises a phase hologram, and the phase information recorded in a certain predetermined  
25 peripheral site of the computer-generated hologram relative to an input pattern reconstructible from the computer-generated hologram is removed.

Preferably in the present invention, the computer-

generated hologram has a phase distribution multivalued to four or more levels.

Preferably in the present invention, the computer-generated hologram is in a rectangular matrix form in which a number of minuscule computer-generated hologram elements having identical characteristics are set together in parallel, and a minuscule computer-generated hologram element is removed from any one of pre-determined four corners of the computer-generated hologram.

Preferably in the present invention, the input image patterns recorded in computer-generated holograms fitted in right and left frames of the viewing device have binocular parallax.

The present invention also provides a computer-generated hologram for a holographic viewing device, which is constructed as a transmission Fourier transform hologram for the holographic viewing device, wherein at least one of phase information and amplitude information recorded in a certain predetermined peripheral site of the computer-generated hologram relative to an input pattern reconstructible from the computer-generated hologram is removed.

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Preferably in the present invention, the computer-generated hologram is in a rectangular matrix form in which a number of minuscule computer-generated hologram elements having identical characteristics are set together in parallel, and a minuscule computer-generated hologram element is removed from any one of predetermined four corners of the computer-generated hologram.

Thus, the present invention provides a computer-generated hologram constructed as a transmission Fourier transform hologram is fitted in a frame member, wherein at least one of phase information and amplitude information recorded in a certain predetermined peripheral site of the computer-generated hologram relative to an input pattern reconstructible from the computer-generated hologram is removed. The site from which the information has been removed can be checked at first glance so that whether or not the top and bottom and the two sides of that computer-generated hologram are properly positioned can immediately be made out. This computer-generated hologram can easily be mounted on a frame such as a spectacle frame in a proper form, so that a given input image pattern can easily be seen properly in place of light sources in a scene.

Still other objects and advantages of the invention will in part be obvious and will in part be apparent from the specification.

The invention accordingly comprises the features of construction, combinations of elements, and arrangement of parts, which will be exemplified in the construction hereinafter set forth, and the scope of the invention will  
5 be indicated in the claims.

#### BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is illustrative in schematic of a computer-generated hologram mounted on the frame of the holographic  
10 spectacles of the invention, and an image area reconstructed from the same.

Fig. 2 is a flowchart of the steps for obtaining the computer-generated hologram of the invention.

Fig. 3 is illustrative in section of one exemplary  
15 construction of the computer-generated hologram of the invention.

Figs. 4(a) and 4(b) are illustrative of how a number of minuscule computer-generated hologram elements having the same characteristics as those of the computer-  
20 generated hologram used for the holographic spectacles of the invention are set together to construct that computer-generated hologram.

Figs. 5(a), 5(b) and 5(c) are illustrative of one specific image according to the invention and a basic  
25 pattern of photomask for implementing phase modulation corresponding to the image pattern.

Fig. 6 is illustrative of one exemplary arrangement of the basic pattern of the photomask constructed from the

basic pattern of Fig. 5.

Fig. 7 is a perspective view of the holographic spectacles having the computer-generated hologram fabricated using the photomask of Fig. 6.

5 Figs. 8(a), 8(b) and 8(c) are illustrative of conventional holographic spectacles and how they work.

#### DESCRIPTION OF THE PREFERRED EMBODIMENTS

Embodiments of the holographic viewing device of the invention and the computer-generated hologram for the same  
10 are now explained.

Fig. 1 is illustrative in schematic of a computer-generated hologram 20 (corresponding to the transmission holograms 2, 3 of Fig. 8(a)) to be mounted on the frame of  
15 the holographic spectacles of the invention, and an image area 30 reconstructed from the same. The computer-generated hologram 20 is a Fourier transform hologram that comprises an array of minuscule cells 21 arranged in a matrix form with a size  $\delta_y$  in the column (y-axis)  
20 direction and a size  $\delta_x$  in the row (x-axis) direction. In this embodiment, each cell has position information alone, as described later. The matrix array has  $2^m$  cells 21 in the x-axis direction and  $2^n$  cells 21 in the y-axis direction..

25 On the other hand, the image area 30 positioned far enough from the computer-generated hologram 20 comprises an array with  $2^m \times 2^n$  cells 31 in the x- and y-directions,

corresponding to the computer-generated hologram 20. Each cell 31 has a size  $\Delta_y$  in the column (y-axis) direction and a size  $\Delta_x$  in the row (x-axis) direction, and the image area 30 has a length  $L_x$  in the x-axis direction and a  
5 length  $L_y$  in the y-axis direction.

The lengths  $L_x$  and  $L_y$  of the image area 30 in the x- and y-axis directions have correlations with the sizes  $\delta_x$  and  $\delta_y$  of the cell 21 of the computer-generated hologram 20 in the x- and y-axis directions, respectively. In  
10 terms of the angle of diffraction from the computer-generated hologram 20 (the image area 30 is positioned far enough from the computer-generated hologram 20, and so the  $L_x$  and  $L_y$  should preferably be given by angle),  $L_x$  corresponds to a range contained in the spreading of the  
15  $\pm$  first-order diffracted light from a diffraction grating having a spatial frequency of  $1/(2\delta_x)$  and  $L_y$  corresponds to a range contained in the spreading of the  $\pm$  first-order diffracted light from a diffraction grating having a spatial frequency of  $1/(2\delta_y)$ . This correspond to the fact  
20 that the maximum spatial frequency recorded in the computer-generated hologram 20 is  $1/(2\delta_x)$  in the x-axis direction and  $1/(2\delta_y)$  in the y-axis direction.

As, in such positions relations, parallel light 15 having a given wavelength enters the computer-generated  
25 hologram 20 from its front, diffracted light 16 occurs on the back surface side of the computer-generated hologram 20, so that a pattern recorded in the computer-generated



hologram 20, for instance, such a letter "F" as described later is reconstructed on the image area 30 far away from the hologram 20. Accordingly, when the computer-generated hologram 20 is used instead of spectacle lenses to view a scene from the front, the user would see the letter "F". Thus, when the computer-generated hologram 20 is used to view such a scene as typically shown in Fig. 8(b), the user would see the pattern "F" in place of light sources 4, 5, 6 and 7.

10           A specific embodiment of how to calculate the phase information of each cell 21 such that the computer-generated hologram 20 reconstructs the pattern "F" is now explained. To impart given diffracted light to a reconstruction image plane, this embodiment relies on a method of calculating a computer-generated hologram to be located on a hologram surface while Fourier transform and inverse Fourier transform are alternately repeated between the reconstruction image plane and the hologram surface with the application of a bound condition. For that method called Gerchberg-Saxton iterative calculation method, for instance, see "Holograms and Diffraction Type Optical Elements - from fundamental theories to industrial applications" used as the text at the 22nd Winter Seminar held by the Optics Society of Japan (the Applied Physics Society of Japan), pp. 36-39.

To help understand the invention, suppose here that  $A_{\text{IMG}}(x, y)$  is the amplitude distribution (pixel value) of

an input image on the reconstruction image plane 30,  $\phi_{\text{IMG}}(x, y)$  the phase distribution of the input image on the reconstruction image plane 30,  $A_{\text{HOLO}}(u, v)$  the amplitude distribution of the input image on the hologram surface 20, and  $\phi_{\text{HOLO}}(u, v)$  the phase distribution of the input image on the hologram surface 20. As shown in Fig. 2, in step (1) the pixel value of the input image to be recorded is given as  $A_{\text{IMG}}(x, y)$  at the reconstruction image plane 30 area to initialize the phase distribution of the input image to a random value, and in step (2), Fourier transform is performed on the initialized value. In step (3), the amplitude distribution  $A_{\text{HOLO}}(u, v)$  on the hologram surface 20, obtained by Fourier transform, is assumed to be unity to give a determined bound condition to make a multivalued phase distribution  $\phi_{\text{HOLO}}(u, v)$  (quantization). After such a bound condition has been imparted, in step (4) inverse Fourier transform is performed on the amplitude distribution  $A_{\text{HOLO}}(u, v)$  and phase distribution  $\phi_{\text{HOLO}}(u, v)$  to which that bound condition is given. If, in convergence judgment step (5), the amplitude distribution  $A_{\text{IMG}}(x, y)$  on the reconstruction image plane 30, obtained through that inverse Fourier transform, is found to be substantially equal to the pixel value of the input image, then the multivalued (quantized) phase distribution  $\phi_{\text{HOLO}}(u, v)$  in step (3) becomes the phase distribution given to the cells 21 of the computer-generated hologram 20. If, in convergence judgment step (5), the amplitude distribution

$A_{\text{IMG}}(x, y)$  obtained through inverse Fourier transform is found to be not equal to the pixel value of the input image, then a bound condition is imparted in step (6) in such a way that the pixel value of the input image is  
 5 imparted in place of the amplitude distribution  $A_{\text{IMG}}(x, y)$  while the phase distribution  $\phi_{\text{IMG}}(x, y)$  obtained through inverse Fourier transform is maintained intact. After such a bound condition has been imparted, a loop of steps  $(2) \rightarrow (3) \rightarrow (4) \rightarrow (5) \rightarrow (6)$  is repeated until the condition for  
 10 step (5) is satisfied or converged, which results in the final desired computer-generated hologram 20.

It is acceptable to perform the given multivalued processing after the condition for step (5) has been satisfied without performing multivalued processing on the  
 15 phase distribution  $\phi_{\text{HOLO}}(u, v)$  in step (3).

The depth distribution of an actual hologram is determined from the thus obtained multivalued phase distribution  $\phi_{\text{HOLO}}(u, v)$ . For such a transmission hologram as used herein, the depth is transformed into the depth  
 20  $D(x, y)$  of the computer-generated hologram 20 on the basis of the following equation (1).

$$D(u, v) = \lambda \phi_{\text{HOLO}}(u, v) / \{2\pi (n_1 - n_0)\} \quad \dots (1)$$

Here  $\lambda$  is the center wavelength used, and  $n_1$  and  $n_0$  are the refractive indices of two materials that form the  
 25 transmission hologram. As shown typically in the sectional view of Fig. 3, a relief pattern 18 having a depth  $D(u, v)$  found from equation (1) is formed on the

surface of a transparent substrate 17 so that the computer-generated hologram 20 of the invention can be obtained. Fig. 3 is illustrative of a specific example of  $\phi_{\text{HOLO}}(u, v)$  multivalued to four levels of 0,  $\pi/2$ ,  $\pi$  and 3  $\pi/2$ . It is here noted the coordinates (u, v) on the hologram surface 20 are provided to make a difference with the coordinates (x, y) on the reconstruction image plane 30, with the u-axis direction corresponding to the x-axis direction and the v-axis direction to the y-axis direction.

10       The thus obtained computer-generated hologram 20 requires an enormous amount of calculation. In actual applications, a minuscule hologram element 20 is first fabricated. Then, a number of such hologram elements 20 are tightly arranged parallel in a desired area into  
15       transmission holograms 2, 3 that are mounted on a spectacle frame 1.

      The reason is that each hologram element 20 is capable of reconstructing the pattern recorded therein in the image area 30 far enough therefrom, and even when the  
20       pupil of the user is obstructed by some hologram elements 20, the viewer could perceive them as one single pattern where they overlap, because the pattern of each hologram element 20 is reconstructed at a position far enough therefrom.

25       Such minuscule computer-generated holograms (hologram elements) 20 having the same characteristics, each of rectangular shape, could be arrayed in a lattice

matrix into the transmission hologram 2, 3, as shown in Fig. 4(a). Alternatively, the hologram elements 20, again each of rectangular shape, could be arranged into the transmission hologram 2, 3 while, as shown in Fig. 4(b), the elements at even-number rows, e.g., the second and fourth rows, are displaced by a half pitch in the row direction. It is noted that the hologram elements 20 are not always limited to square or rectangle, and so they could take on other polygonal forms. To achieve a close array, the hologram elements 20, each of triangular shape, could be arrayed with adjacent elements 20 turned upside down. If the hologram elements 20 are of hexagonal shape, the hologram elements at a certain row could be displaced by a half pitch between the upper row and the lower row, as shown in Fig. 4(b).

As described above, the computer-generated holograms (hologram elements) 20 in the transmission hologram 2, 3 are all the same. To set together such hologram elements 20 as shown in Figs. 4(a) or 4(b) into the transmission hologram 2, 3, it is preferable to rely on a mask for fabricating the transmission hologram 2, 3, wherein photolithographic patterns for the hologram elements 20 are parallel arrayed as shown in Fig. 4(a) or 4(b).

The thus fabricated transmission hologram 2, 3 is mounted on a spectacle frame 1 (Fig. 7). Unless, at this time, the holograms 2 and 3 are mounted on the spectacle frame 1 in such a way that their tops and bottoms and two sides are in proper directions with respect to the

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spectacle frame 1, it is then impossible for the user to have a proper viewing of the pre-selected pattern in a given form. As already described, when the holograms are mounted on the spectacle frame, for instance, with both  
5 sides reversed to reverse the right and left sides while the top and bottom remain intact, the user could see a mirror image in place of light sources in the scene; that is, the user could see a right-hand image as a left-hand image. Conversely, when the top and bottom are reversed  
10 and the right and left sides are reversed while both sides remain intact, the user could see an inverted image; that is, the user could see an erect image as an inverted image in place of light source in the scene.

In one embodiment of the invention, when a number of  
15 identical hologram elements 20 are set together in a lattice matrix into the transmission hologram 2, 3, any one of the hologram elements 20 positioned at four corners is removed to create a mark that help make out the top and bottom and the two sides of the transmission hologram 2, 3  
20 comprising a set of computer-generated hologram elements 20. This embodiment is now explained specifically.

Fig. 5(a) is illustrative of the input image to be recorded in the computer-generated hologram 20 comprising hologram elements. The input image defined by the letter  
25 "F" is divided into  $256 \times 256$  cells, which are then multivalued to the four levels according to the flowchart of Fig. 2, thereby obtaining the computer-generated

hologram 20. Basic photomask patterns for implementing phase modulations  $\pi$  and  $\pi/2$  to the computer-generated hologram 20 are shown in Figs. 5(b) and 5(c), respectively. As is the case with the input image of Fig. 5(a), each photomask pattern is divided into  $256 \times 256$  cells, each having a size of  $5 \mu\text{m} \times 5 \mu\text{m}$ , and has a  $1.28 \text{ mm} \times 1.28 \text{ mm}$  size.

Such basic photomask patterns are used to fabricate photomasks for phase modulations  $\pi/2$  and  $\pi$  by arranging the basic patterns of Figs. 5(b) and 5(c) in a  $16 \times 20$  lattice matrix, thereby fabricating the transmission hologram 2, 3 having a  $20.48 \text{ mm} \times 25.6 \text{ mm}$  size. To help make out the top and bottom and the two sides of the transmission hologram 2, 3 in an easy fashion, one hologram element is removed from the left-upper corner of the lattice matrix, as shown in Fig. 6.

Thus, when a number of identical hologram elements 20 are set together in a lattice matrix, the hologram element is removed from any one (the left-upper corner of Fig. 6 as viewed from the viewer side) of the four corners of that matrix, so that the position from which the hologram element is removed can be checked at first glance to know whether or not the top and bottom or the two sides of the transmission hologram 2, 3 are properly located. As shown in the perspective view of Fig. 7, therefore, the transmission hologram 2, 3 can be mounted on the spectacle frame 1 in a proper form.

Reference is now made to how the phase distribution is multivalued to four levels using the photomask comprising the basic pattern for implementing the phase modulation  $\pi$  of Fig. 5(b) and the photomask for implementing the phase modulation  $\pi/2$  of Fig. 5(c). For instance, when two alignments and etching of a transparent substrate 17 are carried out using a positive resist, alignment operation is performed while an opening in the phase modulation  $\pi$  photomask is superposed on an opening in the phase modulation  $\pi/2$  photomask thereby obtaining a  $3\pi/2$  phase portion; alignment operation is carried out while the opening in the phase modulation  $\pi$  photomask is superposed on a light-shielding portion of the phase modulation  $\pi/2$  photomask thereby obtaining a  $\pi$  phase portion; alignment operation is performed while a light-shielding portion of the phase modulation  $\pi$  photomask is superposed on the opening in the phase modulation  $\pi/2$  thereby obtaining a  $\pi/2$  phase portion; and alignment operation is performed while the shielding portion of the phase modulation  $\pi$  photomask is superposed on the shielding portion of the phase modulation  $\pi/2$  photomask thereby obtaining a 0 phase portion.

In the foregoing embodiment of the invention, a number of hologram elements having the same characteristics, each comprising the minuscule computer-generated hologram 20, are set together in a rectangular matrix form, thereby obtaining the transmission hologram 2,



3, to be mounted on the spectacle frame 1. In this case,  
the hologram element 20 is removed from any one of the  
pre-selected four corners, so that the top and bottom and  
the two sides of the transmission hologram 2, 3 can be  
5 checked. It is understood that when one large computer-  
generated hologram 20 of rectangular shape is constructed  
as the transmission hologram 2, 3, the top and bottom or  
the two side thereof can be checked at first glance by  
allowing the amplitude or phase information to be drawn to  
10 be not recorded in any one of the four corners.

It is here noted that when Fourier transform  
holograms with patterns of binocular parallax recorded in  
them are used as the right eye and left eye transmission  
holograms 2 and 3 to be mounted on the spectacle frame 1,  
15 the user could view a pattern in place of the light  
sources 4, 5, 6 and 7 in such a scene as typically shown  
in Fig. 8(b) as a 3D image. In such cases, the use of the  
computer-generated hologram of the invention that is  
marked in such a way that the top and bottom and the two  
20 sides thereof can be checked at first glance helps  
fabricate and assemble holographic spectacles.

The holographic spectacles of the invention and the  
computer-generated hologram for the same have been  
described with reference to some specific embodiments;  
25 however, various modifications to them are possible. It  
is noted that the computer-generated hologram of the  
present invention is applicable to a holographic monocle  
as well as to windows and displays. The present invention

may also be applied to holograms other than the computer-generated hologram. For instance, to make out the top and bottom and the two sides of other such hologram, it is effective to remove at least one of phase information and amplitude information recorded in a certain predetermined peripheral site of the computer-generated hologram relative to an input pattern reconstructible from that hologram.

As can be appreciated from the foregoing, the present invention provides a holographic viewing device and a computer-generated hologram for the same. Specifically, at least one of phase information and amplitude information recorded in a certain predetermined peripheral site of the computer-generated hologram relative to an input pattern reconstructible from the computer-generated hologram is removed. The site from which the information has been removed can be checked at first glance so that whether or not the top and bottom and the two sides of that computer-generated hologram are properly positioned can immediately be made out. This computer-generated hologram can easily be mounted on a frame such as a spectacle frame in a proper form, so that a given input image pattern can easily be seen properly in place of light sources in a scene.

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